External calibration of GOCE SGG data with terrestrial gravity data: A simulation study

D. N. Arabelos
Department of Geodesy and Surveying, Aristotle University of Thessaloniki, GR-54 124 Thessaloniki, Greece

C.C. Tscherning, M. Veicherts
Department of Geophysics, University of Copenhagen, Juliane Maries Vej 30, DK-2100 Copenhagen Oe, Denmark

Abstract. Terrestrial gravity anomalies selected from three extended continental regions having a smooth gravity field were used in order to determine the appropriate size of the area for gravity data collection as well as the required data-sampling for calibration of the GOCE satellite gravity gradient (SGG) data. Using Least Square Collocation (LSC), prediction of gravity gradient components was carried out at points on a realistic orbit. Based on the mean error estimation it was shown that up to 80% of the signal of the gravity gradient components, as it is expressed through the covariance function of the terrestrial gravity data, can be recovered in the case of an optimal size of the collection area and of the optimum resolution of the data. These optimal conditions e.g. for the Australian gravity field, correspond to an $10^\circ \times 12^\circ$ area extend and a $5'$ data-sampling. It was also numerically demonstrate that it is possible to calibrate the GOCE SGG data for systematic errors such as bias and tilt.

Keywords. Satellite Gravity gradiometer data, External calibration, Systematic error parameters

1 Introduction

In the last decade numerous investigations were published, concerning the calibration of GOCE satellite gravity gradiometer data, (e.g. Baumann et al., 2004, Wolf and Denker, 2004). The use of Least Squares Collocation (LSC) as a element of the space-wise approach methods has also been discussed in a number of papers (e.g. Tscherning, 2003). The aim of this work was to determine the size of required areas with terrestrial gravity data, as well as the required resolution and accuracy of the gravity data needed for calibration when LSC is used. The aim is to detect possible systematic errors in the GOCE SSG data.

The “simple” LSC method was used for the tests concerning the size of the area and the resolution of the data, while the parametric LSC was used for the tests concerning the detection of systematic errors.

The terrestrial gravity data sets used in this study are described in details in section 2. In the first part of this study errors of gravity gradients were computed at points on the realistic orbit of the IAG SC7 simulated data set with the gradients in a reference frame aligned with the velocity vector and the z-axis which lie in the plane formed by this vector and the position vector. In the last part of the study points on a similar orbit were used,but with the gradients given in a more realistic instrument reference frame provided by ESA (R. Floberhagen, private communication 2004).

The precision of the calibration will be directly proportional to the gravity field standard deviation for example expressed as the standard deviation of gravity anomalies from which the contribution of a reference field have been subtracted. The areas studied here are therefore areas with a very smooth gravity field.

We have used EGM96 to degree 360 (Lemoine et al., 1998) for the reduction of gravity anomalies, in order to smooth as far as possible the gravity anomalies used in all test areas. Then, using the reduced gravity anomalies we have predicted gradient values at points on tracks crossing the areas, further on called control points.Since real GOCE data are not yet available we have used the error estimates given by collocation instead of the statistics of the differences between predicted and control values. More specifically, we relate the mean collocation error, depending on the choice of the covariance function, with the formal standard deviation of the gravity gradient components, depending also on the covariance function used, in order to draw conclusions about the optimal size of the area and the resolution of the data needed for the calibration. Note, however, that the error in the middle of the area typically is 90% of the mean error.

It will be numerically shown in the next, that in all test areas, using LSC and terrestrial gravity anomalies, up to 80% of the formal standard deviation of the gravity gradient signal can be recovered, in the case of a high data accuracy, size of the area of collection of terrestrial gravity anomalies and of the data-sampling. Furthermore, it will be also numerically shown that in this way it is possible to calibrate the GOCE SGG data for systematic errors such as bias and tilt. Here we have used that the expected accuracy of 1 s sampled data in the measurement band-with will have an error equal to or above 7 mE.

In the computations it was attempted to keep the data-sampling and the size of the terrestrial data collections areas constant for the corresponding experiments from area to area.

2 Gravity data used

For reasons discussed in earlier work (e.g. Arabelos & Tscherning, 1998), for the requirements of the calibration, the terrestrial data have to be collected from areas with at possible smooth free air gravity anomaly field. A further reason for this is to avoid topographic reductions to smooth the gravity field, due to errors that could be introduced to gravity anomalies from erroneous altitudes and density hypotheses.

Another requirement was to collect data from extended regions in different geographic latitudes due to the dependence of the distribution of the GOCE data on the latitude.

For all these reasons, data from the Canadian plains, Australia and Scandinavia were used.

1. Terrestrial free-air gravity anomalies from the Canadian plains (further on called region A)

This data set was already described in (Arabelos & Tscherning, 1998). In the present paper the reduced values of free-air gravity anomalies to degree 360 were used, within the area bounded by $56° \leq \varphi \leq 68°, 236° \leq \lambda \leq 254°$. The free-air gravity field is shown in Fig. 1. The corresponding statistics is shown in Table 1.

2. Surface gravity anomalies from Australia (further on called region B)

The 2004 edition of the Australian National Gravity Database contains over 1,200,000 point data values in the area bounded by $-48° \leq \varphi \leq -8°, 108° \leq \lambda \leq 162°$. This data was made available by Geoscience Australia. The data set covering the continental Australia and the surrounding ocean (1,117,054 point values) was reduced to EGM96. The statistics of the original and reduced free-air gravity anomalies is shown in Table 1.

As it is shown in Fig. 2 the gravity field is very smooth in the central Australia and consequently, appropriate for the calibration requirements. For this reason, point gravity anomalies were selected from the area bounded by $-32° \leq \varphi \leq -20°, 124° \leq \lambda \leq 144°$.

3. Gravity anomalies from Scandinavian (further on called region C)

Terrestrial as well as air-borne gravity anomaly data sets were made available by R. Forsberg, P. Knudsen and G. Strykovski (private communication). The terrestrial data set (62,126) cover the area $53.99° \leq \varphi \leq 64°, 11.97° \leq \lambda \leq 30.02°$. After the reduction to EGM96 we obtain present the statistics given in Table 1. The air-borne data set cover the area $54.58° \leq \varphi \leq 60.12°, 12.01° \leq \lambda \leq 26.86°$. The statistics of the reduced to EGM96 air-borne gravity anomalies (4778 point values) is shown in Table 1.

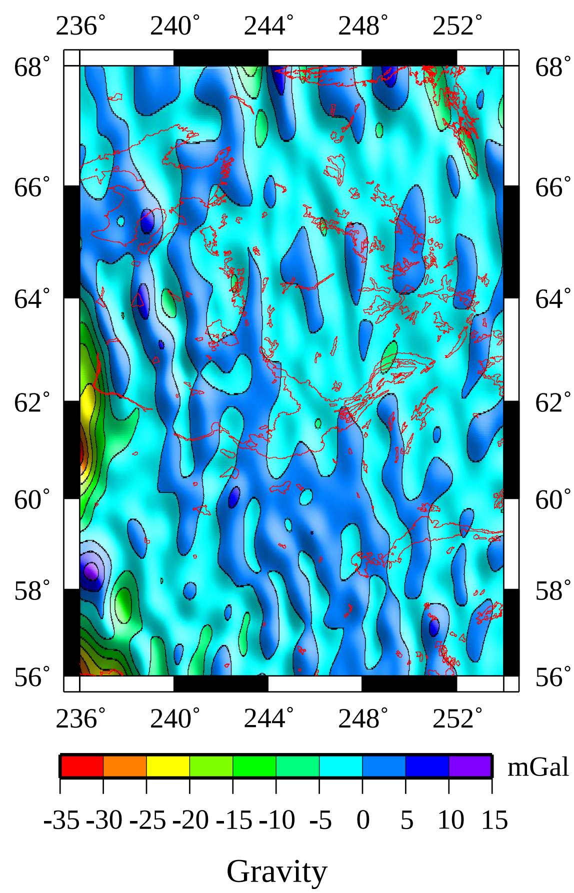

Figure 1. The free-air anomaly-EGM96 gravity field in the Canadian plains (simplified)

Table 1. Statistics of the free-air gravity anomalies used in the regions A, B and C. Unit is mGal

	Observations	EGM96	Difference
Region A, 14,177 point values			
Mean	-10.768	-10.678	-0.090
Standard Dev.	22.419	17.497	13.418
Max. Value	133.000	51.044	114.168
Minimum value	-81.100	-72.210	-124.857
Region B, 1,117,054 point values			
Mean	4.901	5.158	-0.258
Standard Dev.	24.504	22.504	12.102
Max. Value	248.602	94.223	219.875
Minimum value	-211.327	-104.930	-194.732
Region C, 62,126 terrestrial values			
Mean	-8.466	-8.118	-0.349
Standard Dev.	18.285	16.229	8.789
Max. Value	71.740	36.066	76.805
Minimum value	-84.021	-77.351	-47.250
Region C, 4,778 air-borne values			
Mean	-18.443	-19.735	1.292
Standard Dev.	19.834	18.209	10.024
Max. Value	29.660	21.235	35.085
Minimum value	-80.540	-68.107	-31.675

Table 2. Signal standard deviation of data at the control points used in the numerical experiments. (E)

	Region A	Region B	Region C
T_{xx}	0.0042	0.0035	0.0047
T_{xy}	0.0049	0.0041	0.0054
T_{xz}	0.0050	0.0042	0.0056
T_{yy}	0.0042	0.0035	0.0047
T_{yz}	0.0050	0.0042	0.0056
T_{zz}	0.0072	0.0060	0.0079

In the collocation experiments both data sets were used jointly with common accuracy equal to 2 mGal. The free-air gravity field reduced to EGM96 is shown in Fig. 3.

From Table 1 it is shown that the reduced to EGM96 free-air gravity anomalies present very similar statistical characteristics. This is more evident from the shape of the corresponding covariance functions (see Fig. 4).

For the reasons discussed in section 1 the formal standard deviation of the control values used in the numerical experiments of section 3 is shown in Table 2 for the three test regions. This formal standard deviation for each area is based on the corresponding covariance function of Fig. 4.

3 Numerical Experiments

3.1 Tests concerning the required size of the area and the resolution of the data

The experiments concern recovery of 5 s sampling noise-free simulated GOCE data provided by IAG, along 1 month realistic orbit (250 km), using terrestrial gravity anomalies. For the determination of the required size of the area for terrestrial data collection in all cases 10 arcmin data-sampling was used and prediction experiments were carried out in four areas with different size. For the determination of the required data-sampling, the prediction experiments

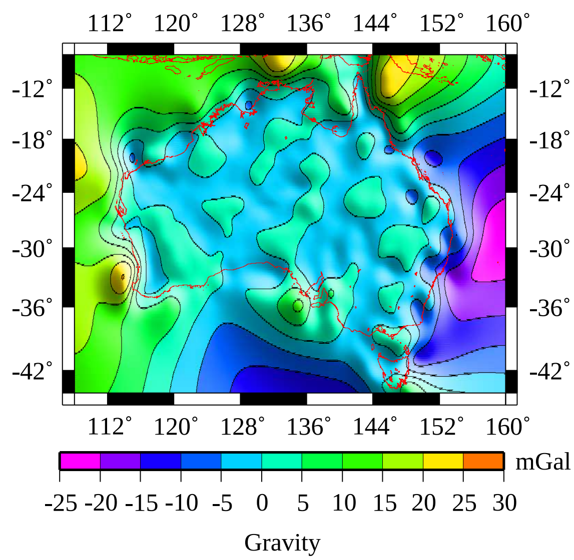

Figure 2. The free-air anomaly-EGM96 gravity field in Australia (simplified)

were carried using data with 5, 7.5, 10, 15 and 20 arcmin. sampling in areas with constant size. In all computations the GRAVSOFT programs (Tscherning et al., 1992) EMPCOV, COVFIT and GEOCOL were used.

Region A

Simulated GOCE data used as control data in the area $58.5° \leq \varphi \leq 63.5°, -118° \leq \lambda \leq 112°$, (242 values). The covariance function of gravity anomalies used (empirical and the corresponding analytical one is shown in Fig. 4 (upper).

(a) Experiments for the determination of the size of the area for terrestrial data collection

The experiments were carried out using terrestrial gravity data with constant 10 arcmin sampling. Accuracy equal to 1 mGal was adopted for these data.

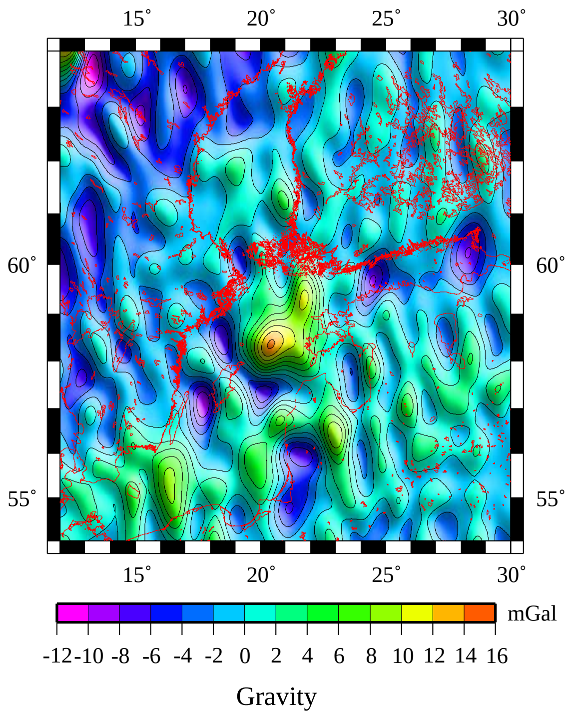

Figure 3. The free-air anomaly-EGM96 gravity field in Scandinavia (simplified)

Prediction experiments were carried out collecting terrestrial data from four areas with size $5^\circ \times 6^\circ, 6^\circ \times 8^\circ, 8^\circ \times 10^\circ$ and $10^\circ \times 12^\circ$ respectively. The first of them correspond to size of the control points collection area. The results of these numerical experiments in terms of the mean collocation error estimation are shown in Fig. 5.

It is well known that the assessment of the prediction results in collocation may be based not only on the statistics of the differences between observed (control) and predicted quantities, but also on the collocation error estimation of the prediction. Since we do not yet have any real GOCE data used the formal error estimates.

With the increase of collection area from $5^\circ \times 6^\circ$ to $10^\circ \times 12^\circ$ a continuous improvement of the mean error estimation concerning all gradient components is shown in Fig. 5. This improvement is more significant in the case of T_{zz} (39%). The mean error of 0.0027 EU correspond to a 37% of the formal standard deviation of T_{zz} (see Table 2 Region A), resulting from the covariance function of free-air gravity anomalies in this region. This could be interpreted as the ability of the method to recover the 63% of the signal, in the case of real SGG data.

(b) Experiments for the determination of data-sampling

Concerning the determination of the required data-sampling, experiments were carried out with terrestrial data collected from the same $6^\circ \times 8^\circ$ area ($58^\circ \leq \varphi \leq 64^\circ, -119^\circ \leq \lambda \leq -111^\circ$) but with different resolution (5, 7.5, 10, 15 and 20 arcmin). The results of these experiments are shown in Fig. 6

From Fig. 6 it is shown that for the same size of the test area, the mean collocation error estimation was decreased with increasing resolution of the data, for all the gravity gradient components. The decrease is more evident in the case of T_{zz} because it drops from 0.0050 to 0.0032 EU when the resolution was

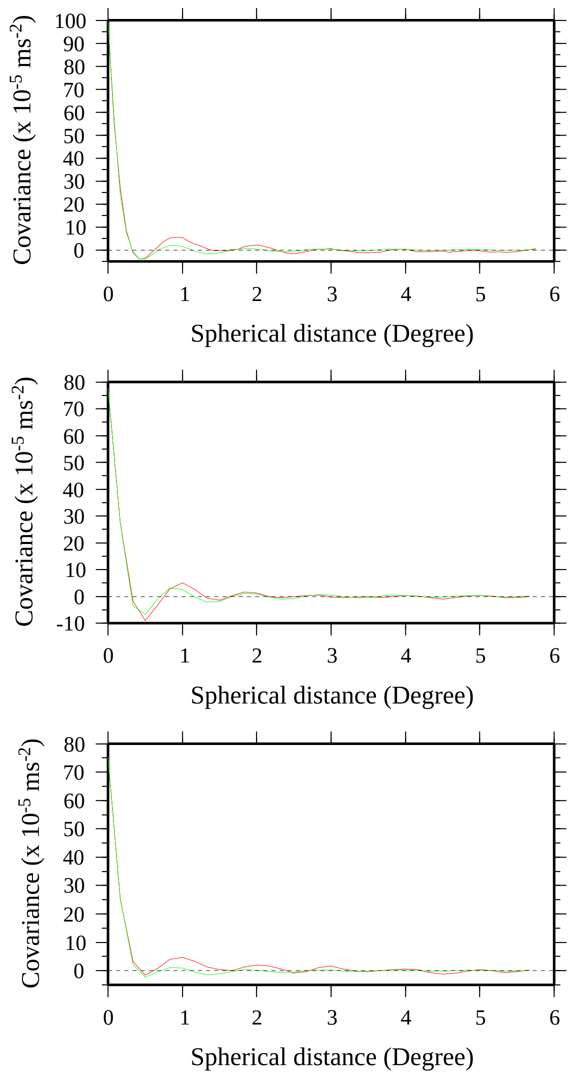

Figure 4. Covariance function of free-air gravity anomalies in the regions A (upper), B (middle) and C (below). Red=empirical, Green=model.

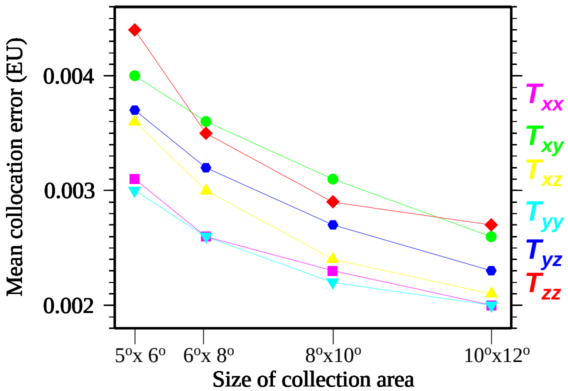

Figure 5. Region A: Mean collocation error estimation for different sizes of the area for terrestrial data collection.

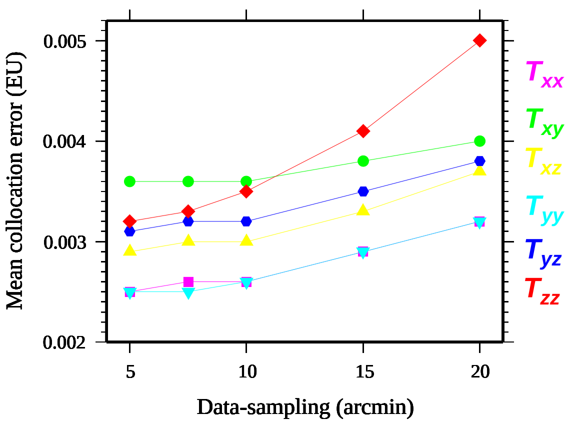

Figure 6. Region A: Mean collocation error for different data-sampling.

increased from 20 to 5 arcmin. In terms of percentage of the formal standard deviation of T_{zz} this correspond to a change from 69% to 44%.

Region B

Experiments were carried out with constant 10 arcmin. data-sampling. The empirical covariance function shown (together with its analytical fitting) in Fig. 4 (middle) was computed from the 10 arcmin gravity data covering the area $-32° \leq \varphi \leq -20°, 124° \leq \lambda \leq 144°$.

The simulated GOCE data were collected from the area $-30.50° \leq \varphi \leq -25.50°, 127° \leq \lambda \leq 133°$ (245 values).

The terrestrial data were assumed to be accurate to 1 mGal.

(a) Experiments concerning the size of required area with terrestrial gravity data

The experiments were carried out using terrestrial gravity data with constant 10 arcmin sampling. Prediction experiments were carried out collecting terrestrial data from four areas with size $5° \times 6°, 6° \times 8°, 8° \times 10°$ and $10° \times 12°$ respectively. The first of them correspond to size of the control points collection area. The results of the prediction in terms of the mean collocation error estimation are shown in Fig. 7.

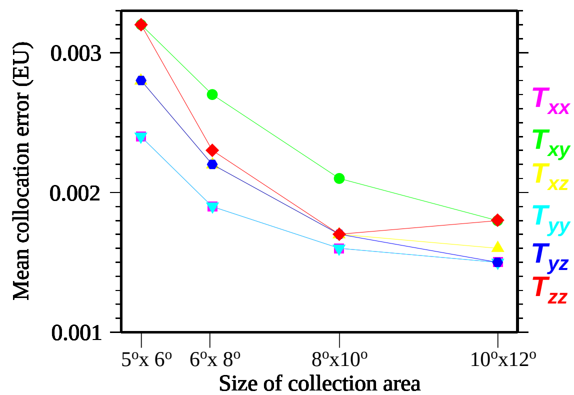

Figure 7. Region B: Mean collocation error estimation for different sizes of the area for terrestrial data collection.

In the region B the formal standard deviation of T_{zz} is 0.0060 EU when the covariance function is computed from terrestrial gravity anomalies in the area $-32° \leq \varphi \leq -20°, 124° \leq \lambda \leq 144°$, while is increased to 0.0089 EU when the covariance function is computed from terrestrial data in the area $-30.50° \leq \varphi \leq -25.50°, 127° \leq \lambda \leq 133°$. From this point of view, the mean collocation error estimation should be considered as a measure of the part of the real signal that could be recovered, if of course, the covariance function used reflects the statistical characteristics of the real signal.

From Fig. 7 it is shown that e.g. in the case of T_{zz}, the mean collocation error is rapidly changing from 54% to 31% of the formal standard deviation of T_{zz}, when the size of the collection of terrestrial data was increased from $5° \times 6°$ to $10° \times 12°$. This means that with an area extent of $10° \times 12°$ about 65% of the signal of the real data could be recovered, which is a value acceptable for the calibration requirements.

(b) Experiments concerning the data-sampling

Terrestrial gravity anomalies with data-sampling 5, 7.5, 10, 15 and 20 arcmin were collected from the area bounded by $-32° \leq \varphi \leq -20°, 124° \leq \lambda \leq 144°$. The prediction results in terms of mean collocation error are shown in Fig. 8.

Table 3. Results of experiments in the region (B) with data-sampling 20', showing that further increase of the size of data collection area has no significant effect. (E)

Comp.	Area extent	Control points	Mean coll. err.
T_{zz}	$6^\circ \times 8^\circ$	436	0.0043
T_{zz}	$10^\circ \times 12^\circ$	982	0.0041
T_{zz}	$12^\circ \times 20^\circ$	2163	0.0041

Table 4. Improvement of the mean error in region (B) when terrestrial gravity anomalies with $10'$, $7.5'$ and $5'$ sampling are used in the same ($10^\circ \times 12^\circ$) area. (E)

Comp.	Data-sampl.	Control points	Mean coll. err.
T_{zz}	$10'$	3879	0.0018
T_{zz}	$7.5'$	6834	0.0014
T_{zz}	$5'$	13476	0.0012

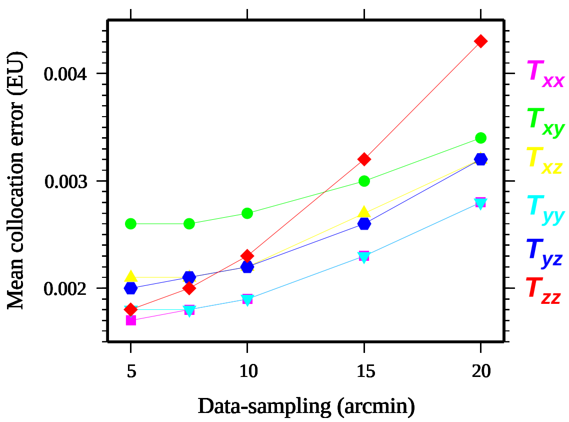

Figure 8. Region B: Mean collocation error for different data-sampling.

From Fig. 8 it is shown that the mean error of estimation for the same size of the area of collection of terrestrial gravity anomalies was decreased when the density of the data was increased, for all the gravity gradient components. In terms of percentage of the formal standard deviation of the various components this decrease is more significant in the case of T_{zz} , since it drops from 71% to 30% as the data-sampling changes from 20 to 5 arcmin. As it is shown in another experiment (see Table 3), a further increase of the size of the area in the case of 20' data-sampling, has no significant effect on the prediction results e.g. of T_{zz}.

Combining the results shown in Figs. 7 and 8 it is reasonable to expect that using data in the larger area ($-33^\circ \leq \varphi \leq -23^\circ, 124^\circ \leq \lambda \leq 136^\circ$) of Fig. 7 with the more dense data-sampling of Fig. 8 we will get the better results in terms of the mean collocation error estimation. This was verified with a relevant experiment (see Table 4)

Region C

The empirical covariance function shown (together with its analytical fitting) in Fig. 4 (below) was computed from gravity data covering the area $54^\circ \leq \varphi \leq 64^\circ, 12^\circ \leq \lambda \leq 30^\circ$.

Simulated GOCE data were collected from the area bounded by $57^\circ \leq \varphi \leq 62^\circ, 21^\circ \leq \lambda \leq 27^\circ$ (250 values) in order to be used as control data. For these data accuracy equal to 0.001 EU was adopted. The statistics of the simulated GOCE data used as control values is shown in Table 14.

(a) Experiments concerning the size of required area with terrestrial gravity data

The experiments were carried out using terrestrial gravity data with constant 10 arcmin sampling. Accuracy equal to 2 mGal was adopted for these data. Prediction experiments were carried out collecting terrestrial data from four areas with size $5^\circ \times 6^\circ, 7^\circ \times 8^\circ, 9^\circ \times 10^\circ$ and $10^\circ \times 12^\circ$, respectively. The first of them correspond to size of the control points collection area. The results of these numerical experiments are shown in Fig. 9

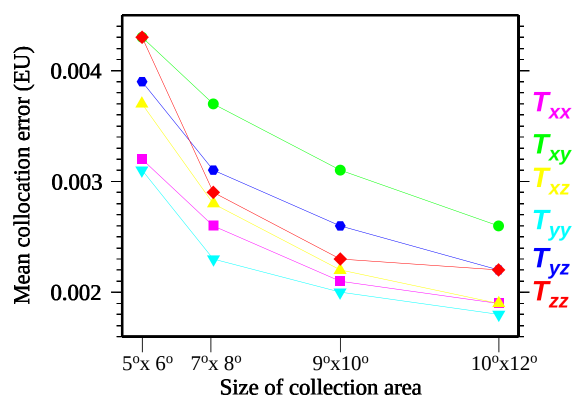

Figure 9. Region C: Mean collocation error estimation for different sizes of the area for terrestrial data collection.

These results are very similar to the previous ones in Tables 6 and 9. Increasing the collection area from $5^\circ \times 6^\circ$ to $10^\circ \times 12^\circ$, the mean error estimation, e.g. in the case of T_{zz} was decreased up to 51% of its original value. In terms of percentage on the formal standard deviation of T_{zz} the mean estimation error drops from 53.8% to 27.5%.

Table 5. GOCE data used for the estimation of systematic parameters

Region	Area extent	No of tracks
A	$56° \le \varphi \le 66°, -122° \le \lambda \le -112°$	40
B	$-33° \le \varphi \le -23°, 124° \le \lambda \le 136°$	41
C	$54° \le \varphi \le 64°, 18° \le \lambda \le 30°$	42

Table 6. Results of the estimation of systematic parameters

Component	Bias EU	Tilt EU/s	Scale fac.
Region A			
T_{xx}	0.006467	0.000250	0.000003
T_{xy}	0.007859	0.000300	0.000496
T_{xz}	0.007794	0.000300	0.000874
T_{yy}	0.007795	0.000298	0.000004
T_{yz}	0.007850	0.000299	0.000159
T_{zz}	0.007975	0.000303	0.000002
Region B			
T_{xx}	0.004273	0.000138	0.000003
T_{xy}	0.005299	0.000169	0.000182
T_{xz}	0.005152	0.000166	0.000563
T_{yy}	0.005234	0.000167	0.000003
T_{yz}	0.005219	0.000167	0.000034
T_{zz}	0.005239	0.000167	0.000002
Region C			
T_{xx}	0.002914	0.000143	0.000003
T_{xy}	0.003883	0.000178	0.000353
T_{xz}	0.003439	0.000170	0.000400
T_{yy}	0.003717	0.000175	0.000004
T_{yz}	0.003637	0.000173	0.000081
T_{zz}	0.003511	0.000170	0.000002

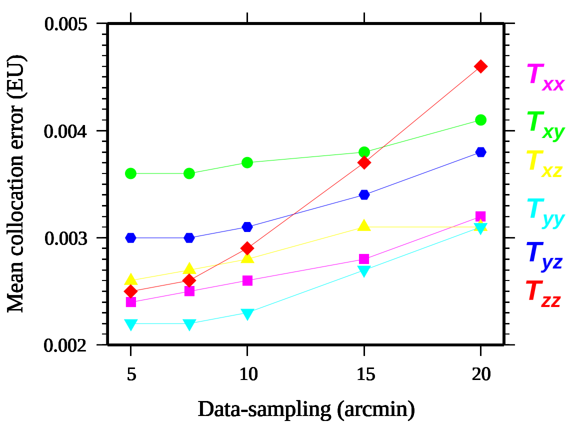

Figure 10. Region C: Mean collocation error for different data-sampling.

(b) Experiments concerning the requirements in data-sampling

For this purpose terrestrial gravity anomalies with data-sampling 5, 7.5, 10, 15 and 20 arcmin were collected from the area bounded by $56° \le \varphi \le 63°, 28° \le \lambda \le 28°$. The prediction results are shown in Fig. 10

Also these results are similar to the results of corresponding experiments in the regions A and B.

3.2 Tests concerning the detection of systematic errors

As it was stated in section 1, the parametric LSC was used for the detection of systematic errors. In order to estimate bias, tilt and scale factor parameters using collocation the possibility for the determination of scale factors was added in the GRAVSOFT program GEOCOL. The systematic parameters were estimated relative to EGM96 “observations” according to the following equation (Moritz, 1978)

$$S = S_{GOCE} + AX + \sigma. \qquad (1)$$

In (1) S represent an (anomalous) gravity gradient component, S_{GOCE} stand for GOCE simulated (anomalous) component, and $A = 1$ when X represent a bias, $A = dt$ when X represent a tilt and $A =$ the un-reduced gradient component when $1 - X$ is a scale factor. Finally, σ stand for a random error.

Because bias and scale factor are very strongly correlated, it does not make sense to estimate both simultaneously. Therefore, the estimation of scale factors was carried out separately from the estimation of the bias and tilt.

The estimation of the parameters was carried out trackwise. For each region the tracks which lie within the borders shown in Table 5 were taken into account. The ”data” were regarded as having along-track correlated errors with error-covariance functions derived from the expected noise power density spectrum.

The results in terms of the mean collocation error estimation of the systematic parameters in the 3 test regions are shown in Table 6. Note that the mean error of the estimated bias parameters in all cases are below 8 mE.

4 Conclusion

Extended prediction experiments were carried out using terrestrial gravity anomalies from the Canadian plains, from Australia and from Scandinavian, in order to determine the appropriate size of the area for gravity data collection as well as the required data-sampling for calibration of the GOCE SGG data.

The experiments concerning the size requirements showed that in all regions the mean error of estimation was continuously decreasing up to 35% (in average) when the size of the area was continuously increased from $5^\circ \times 6^\circ$ to $10^\circ \times 12^\circ$. This $10^\circ \times 12^\circ$ size is considered satisfactory since according to the mean error of estimation a 70% of the signal of the real data can be recovered by the method used.

In the same way, the results of the experiments for the determination of the required resolution of the terrestrial gravity data showed that for constant size $6^\circ \times 8^\circ$ of the collection area, when the data-sampling was changed from $20'$ to $5'$, the mean error of estimation dropped up to 50% (in average) of its original value. In this case, the mean error estimation of T_{zz} correspond to 30% of its formal standard deviation.

More sensitive in both cases (size of collection area as well as data-sampling) is T_{zz}. It was expected, since it has the largest (signal) standard deviation comparing to the other components of the gravity gradients.

However, the combination of $5'$ data-sampling in an $10^\circ \times 12^\circ$ area results in a mean error estimation that drops further up to 20% of the formal standard deviation of T_{zz}. Hence, by selecting the optimal area extend and data sampling we are much below the expected noise level in the measurement band-with.

Finally, using parametric LSC it was shown that the estimation of systematic errors such as bias and tilt in the SGG data is possible using a combination of terrestrial and satellite data. Here again the error of the estimated biases are at the level or below the error in the measurement band-with. The estimation of tilts (drifts) is however above the error if one considers that it takes between 100 and 200 s for GOCE to cross one of the areas. The scale factors of the diagonal elements are also at the error level, considering that the absolute value of the gravity gradients does not exceed 3000 E.

The determination of systematic parameters bias, tilt and scale factor was carried out using least squares collocation. For this purpose the possibility to determine a scale factor was implemented in the GRAVSOFT program GEOCOL. However, an off-line estimation of scale-factors, which has been used for CHAMP accelerometer data (Howe et al., 2003) might be a good alternative.

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